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EXPERIMENTAL STUDY OF WATER FLOW IN ANNULAR PIPES

By W. M. Owen

HYDRAULICS DIVISION

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Power	48, 55, 56, 69, 71, 88 (Discussion: D-XXIII, D-2, D-3, D-7, D-11, D-19, D-25-K, D-17, D-30, D-38, D-40)
Sanitary Engineering	55, 56, 87 (Discussion: D-10, D-29)
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Surveying and Mapping	50, 52, 55, 60, 63, 65, 68
Waterways	41, 44, 45, 50, 56, 57, 70, 71 (Discussion: D-XXVII, D-9, D-8, D-19, D-27, D-28)

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

EXPERIMENTAL STUDY OF WATER FLOW IN ANNULAR PIPES

By W. M. Owen[1]

Synopsis

Head loss and velocity distribution measurements were made on three annular pipes formed by centrally supporting pipe cores in outer pipes. Knowledge of flow conditions in pipes of this type is important in many engineering applications. The fluid used in the tests was water, and the range of Reynolds numbers tested was from 4,000 to 700,000. A description is given of the apparatus used and the precautions taken to assure conformity to the test conditions.

The test results are analyzed and compared with previous research in this field, and conclusions are drawn regarding flow conditions to be expected in actual applications.

Introduction

Knowledge of the head loss and velocity distribution for the turbulent flow of fluids in the annular space between two coaxial cylindrical pipes is important in various engineering problems, especially in those encountered in the oil-producing industries in which pipes of this type are in common use. In this paper such pipes will be referred to as annular pipes; the inner pipe will be called the core, and the outer pipe alone, without the core, will be referred to as a circular pipe. The investigation that is reported herein was conducted to reconcile the conflicting results reported in various investigations listed in the bibliography and to obtain reliable results, especially with respect to the head loss and velocity distribution for turbulent flow in annular pipes of substantial sizes and high rates of flow.

Notation.—The letter symbols used in this paper are defined where they first occur and are assembled in Appendix I for convenience of reference.

Note.—Written comments are invited for publication; the last discussion should be submitted by March 1, 1952.

[1] Research Asst. Prof., Theoretical and Applied Mechanics, Univ. of Illinois, Urbana, Ill.

Test Conditions

Range of Tests.—One brass and two steel annular pipes were used in the investigation. The brass annular pipe consisted of an outer pipe having a nominal inner diameter (d_1) of 2 in. and an inner pipe or core having a nominal outer diameter (d_2) of $\frac{1}{2}$ in. (ratio $d_1/d_2 = 2.47$). One steel annular pipe used in the test consisted of an outer pipe having a nominal diameter of 6 in. and a nominal core diameter of 2 in. ($d_1/d_2 = 2.55$). The other steel annular pipe consisted of the same 6-in. outer pipe but had a core with an outside nominal diameter of 3 in. ($d_1/d_2 = 1.76$). Head loss and velocity determinations were made while water flowed through the pipes at Reynolds numbers varying from 4,000 to 700,000. The water entered the annular pipes from a standpipe that maintained a constant head of approximately 60 ft. Head loss measurements were also made on the outer pipes without the core so that a comparison of the head loss for annular and circular pipes could be made.

The characteristics of laminar flow in annular pipes were not investigated, mainly because of the difficulty in measuring the small values of head loss and velocity. Furthermore, theoretical expressions for the velocity and the rate of discharge for laminar flow in annular pipes have been given by H. Lamb (8)[2] and confirmed experimentally by F. C. Lea and A. Tadros (9) for annular pipes with values of the ratio d_1/d_2 of approximately the same magnitude (1.75–2.5) as those of the test pipes used in this investigation. This range includes the values of the ratio d_1/d_2 of annular pipes that are in general use. However, it was found by Messrs. Lea and Tadros that, for considerably higher values of the ratio d_1/d_2, the experimental results for laminar flow did not agree satisfactorily with those obtained from the theoretical expressions. For example, it was found that for $d_1/d_2 = 23.0$ the theoretical values of the quantity flowing were 26% less than the experimental values. This difference in results has been attributed to turbulence adjacent to the surface of the core.

Description of Apparatus

Six-Inch Steel Pipe.—A diagrammatic sketch representing the apparatus used to test the 6-in. annular pipe is shown in Fig. 1(*a*). The outer circular pipe consisted of five lengths or sections of 6-in. steel pipe, each approximately 20 ft in length. The actual inside diameter of the pipe was 6.06 in. Piezometer rings were placed between the pipe flanges at places where two sections of pipe were joined, and the piezometer rings were connected to a 4-column manometer by means of which the head loss for any one or for all of the 20-ft sections of pipe could be measured. The gage fluids used were mercury (specific gravity 13.56), carbon tetrachloride (specific gravity 1.595) and a mixture of carbon tetrachloride and gasoline (specific gravity 1.23). The gage fluid in the manometer was changed to a lighter fluid whenever the difference in levels of the gage fluid columns was so small as to cause appreciable errors in reading the manometer. Each of two galvanized steel cores (2.375-in. and 3.499-in. outisde diameter) was placed inside the 6-in. pipe and supported and centered by means of metal spiders that also served as connections for the

[2] Numbers in parentheses, thus: (8), refer to corresponding items in the Bibliography (see Appendix II)

core sections. The spiders were located downstream from the region of pressure or pitot tube connections to minimize disturbances that might affect the measured values of pressures or velocities. Both cores consisted of sections 10 ft long and both started at the upstream end of the first section of 6-in. pipe and extended to within 10 ft of the end of the last section of the pipe.

The discharge was controlled by a gate valve located at the downstream end of the last section of pipe, and discharge was measured by means of a calibrated 90° V-notched weir. The first section of pipe was connected to the laboratory standpipe as shown in Fig. 1. Straightening vanes were placed

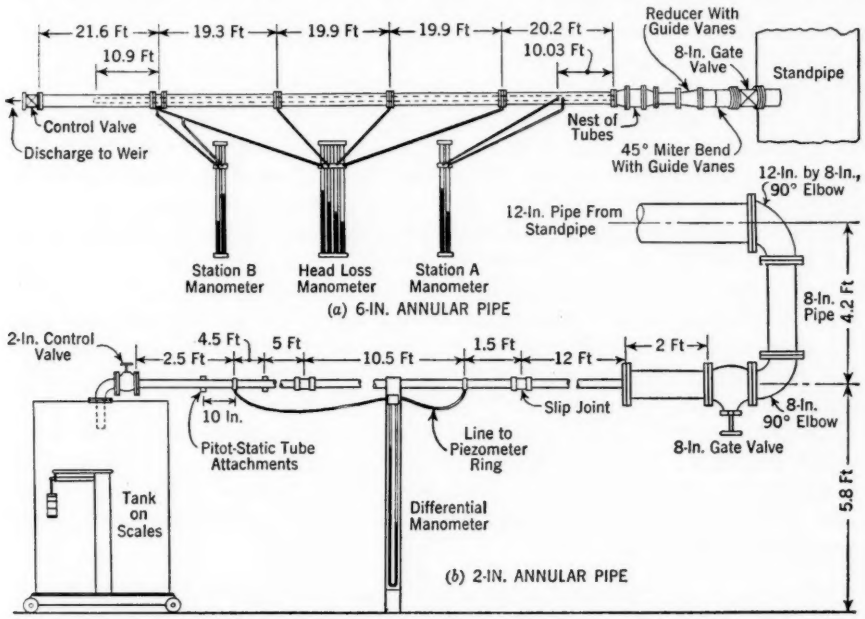

FIG. 1.—ARRANGEMENT OF TEST APPARATUS

in the elbow and reducer, and the straightening section consisted of a nest of tubes. These measures were designed to eliminate spiral motion of the water and produce a uniform velocity distribution in the test pipe. A constant head of approximately 60 ft was maintained on the test pipes by means of a skimming weir located at the top of the standpipe.

Pitot tube stations for making velocity traverses were located in the first and last sections of pipe. Provisions were made to take velocity traverses in the radial direction at diametrically opposite points at both pitot tube stations and the pitot tube traverses at the second station were made at 90° to those at the first station. Static pressure connections at the pitot tube stations were made by drilling several holes in the 6-in. pipe, connecting the holes to a piezometer ring, and connecting the piezometer ring to one side of the pitot tube differential manometer. The pitot tubes were kept in alinement with the axis of the pipe by rotating the tube so that a vane mounted on the tube outside the pipe was parallel to the pipe.

Two-Inch Brass Pipe.—A diagrammatic sketch representing the 2-in. annular pipe apparatus is shown in Fig. 1(*b*). The core is not shown in this sketch. The outer pipe consisted of smooth brass pipe composed of three sections, each 12 ft long with an actual inside diameter of 2.075 in. The couplings connecting the three sections of pipe were of the sleeve type that permitted the ends of the pipes to butt against one another and held the pipes in alinement. The core consisted of 6-ft sections of $\frac{1}{2}$-in. diameter (0.840-in. actual outside diameter) smooth brass pipe. The core was supported and centered within the pipe by means of spiders. The core was fastened to the spiders by pins which fixed the ends of the core and tended to reduce the deflection of the core to a minimum. The maximum deflection of the core which occurred at the midpoint of the length of the core was calculated to be 3% of the distance between the core and pipe wall.

The core extended the entire length of the pipe and was designed to eliminate the placing of a spider near a manometer ring. The test apparatus consisted of an approach section of 13.5 ft of pipe, leading from an 8-in. standpipe supply line, followed by a test section of 20.0 ft. The pressure drop in the test section was measured by means of a differential manometer. The pressure connections to the pipe were made by drilling four holes, 0.1 in. in diameter, at right angles in the pipe. All burrs were carefully removed from the piezometer holes that led into the piezometer ring from which the connection to the manometer was made. The rate of discharge was obtained by measuring the time necessary to collect a given weight of water in a tank mounted on a calibrated scale.

Velocity measurements were made by means of a pitot-static tube of $\frac{1}{8}$-in. outside diameter. The pitot-static tube was connected to the same differential manometer as that used for the head loss measurements. Three gage fluids were used so that the manometer could be read accurately throughout the range of test conditions.

Interpretation of Test Results

Head Loss.—A dimensional analysis of the flow in an annular pipe reveals that the friction factor is a function of the dimensionless ratios Vd_1/ν, d_1/d_2, ϵ_1/ϵ_2, and ϵ_2/d_1. For each pipe used in this investigation the variation of the friction factor with the dimensionless ratio Vd_1/ν can be determined from the Stanton diagram, Fig. 2. The ratio Vd_1/ν for any annular pipe is equal to a constant times the Reynolds number ($4VR/\nu$) shown as abscissas in Fig. 2. If the diameter of the core in an annular pipe is increased and all other factors remain constant, the values of the last two of the foregoing ratios remain constant, but the values of the ratios d_1/d_2 and Vd_1/ν change. From the dimensional analysis result shown above, the Stanton diagram for the flow in annular pipe should consist of several distinct families of curves. Each family of curves would be expected to represent a different hydraulic roughness and each curve in the family a different value of the ratio d_1/d_2.

Fig. 2 shows this expectation to be true for the pipes used in the investigation and also for the pipes tested by F. R. Lorenz (11). The dependence of the friction factor on the ratio d_1/d_2 indicates that average curves showing the

relation between the friction factor and Reynolds number (such as those given by D. H. Atherton (1) and A. P. Kratz, H. J. MacIntire, and R. E. Gould (7)) are unreliable. The curves showing the relation between friction factor and Reynolds number for annular pipe given by Messrs. Kratz, MacIntire, and Gould fall below the curve for the circular pipe without a core and are not in order of the values of the ratio d_1/d_2. This was probably caused by the short initial section used in the test pipes. In general, it can be said that the curves showing the relation between the friction factor and Reynolds number lie above and approximately parallel to the curve for circular pipe of the same roughness, and their range is in the order of the values of the ratio d_1/d_2. The curve of J. Caldwell's data is reproduced in Fig. 2 to show the gradual transition

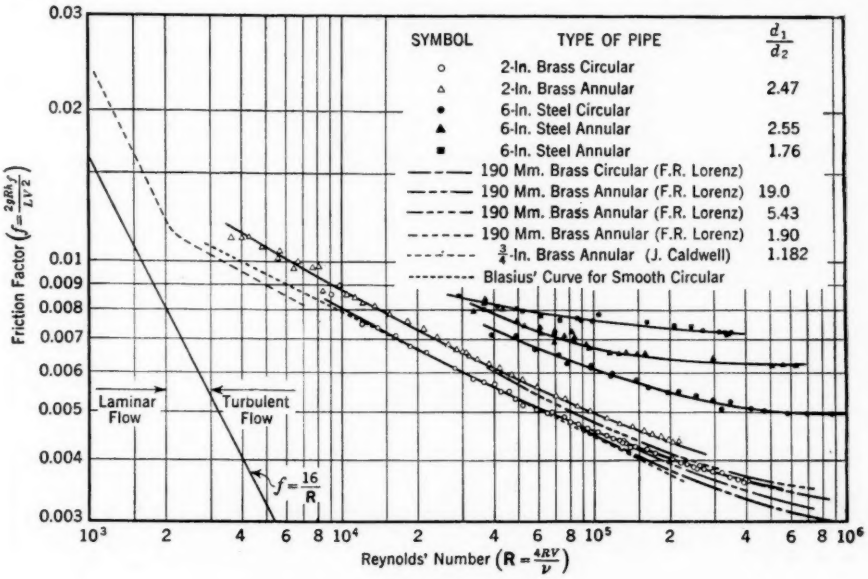

FIG. 2.

from laminar to turbulent flow noted by several experimenters and also to show another experimentally confirmed fact that the transition from laminar to turbulent flow for annular pipe occurs at the same value of Reynolds number as for circular pipe when the Reynolds number is based on the mean hydraulic radius. It should be pointed out that the calculations of the friction factors in Fig. 2 are based on the mean hydraulic radius and, therefore, are only $\frac{1}{4}$ the value given when the diameter is used.

Velocity Distributions in Annular Pipes.—The results of the velocity traverses in annular pipes are shown in Figs. 3 through 6. Fig. 3 shows typical velocity distribution curves for various velocities in the three annular pipes used in this investigation. It should be noted that the velocity distribution curves for corresponding velocities in the three annular pipes are similar in form and are quite flat for the lower velocities, becoming more pointed for increasing velocity. The position of the point of maximum velocity remains

constant within the limits of experimental error, for a given annular pipe. From the velocity distribution curves it is also noted that the point of maximum velocity is nearer to the core than to the pipe wall and that the velocity next to the core is always greater than that next to the pipe wall. This is in disagreement with the results of V. Mikrjukov (12) but agrees with the results of Mr. Lorenz (11).

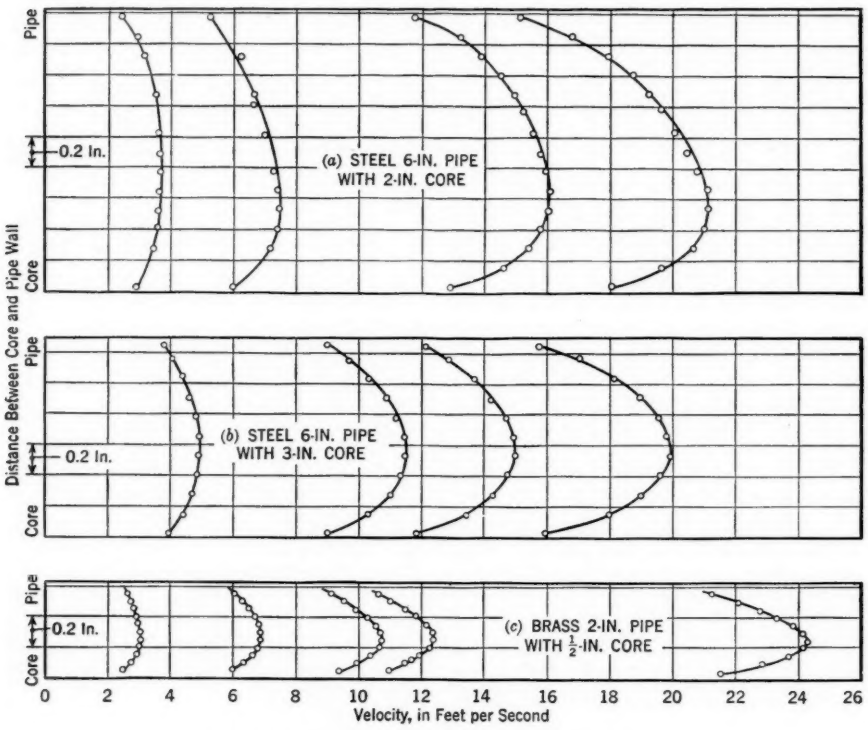

FIG. 3.—VELOCITY TRAVERSES IN ANNULAR PIPE

Fig. 4 is a graph showing the relation between the dimensionless ratios v/V_{max} and $y/r_1 - r_2$ for the 2-in. brass annular pipe for all the velocity traverses. No curves are drawn through the points shown, for the reason that the individual curves would not be distinguishable since the points for the various velocities fall in a very narrow band. However, the points adjacent to the core lie in the same order as the velocities, with one exception, thus indicating a dependence of the velocity distribution curve on the Reynolds number. This fact is in contradiction to a conclusion made by Mr. Lorenz in which he states that in a dimensionless velocity distribution curve, such as the one shown in Fig. 4, the dependence of the velocity distribution curve on the Reynolds number vanishes. The dependence of the velocity distribution curve on Reynolds number was also noted in the two 6-in. steel annular pipes used in the investigation reported herein. The fact that the points in Fig. 4 converge in

the region of the maximum velocity is an indication that the point of maximum velocity for geometrically similar annular pipes remains constant.

Fig. 5 shows dimensionless velocity distribution curves obtained by plotting the ratios v/V_{max} and $y/r_1 - r_2$ for three annular pipes used in this investigation. The curves shown in Fig. 5 are velocity distribution curves obtained by averaging the values of v/V_{max} for the various velocities in each annular pipe. The effect of the roughness on the shape of the velocity distribution curve is clearly shown by examining the velocity distribution curves for the 2-in. brass pipe with a $\frac{1}{2}$-in. brass core and the 6-in. steel pipe with the 2-in. steel core. These

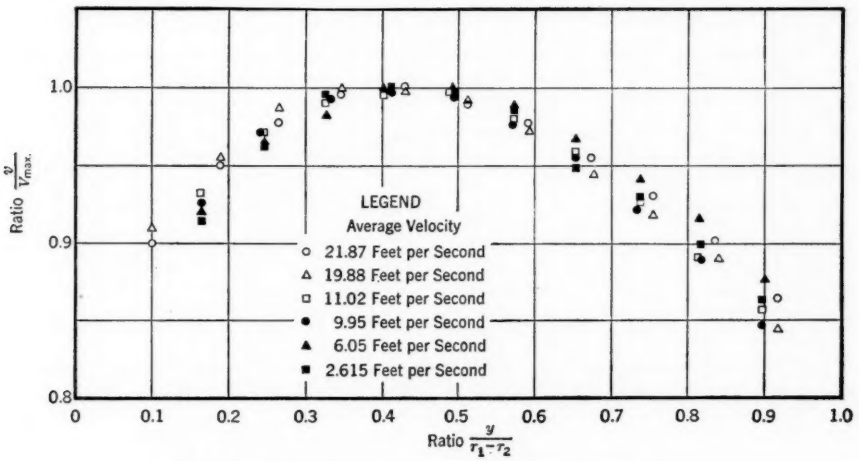

FIG. 4.—DIMENSIONLESS VELOCITY DISTRIBUTION CURVES

annular pipes have approximately the same d_1/d_2 ratios, but they vary considerably in roughness. The velocity distribution curve for the steel annular pipe has a much more elongated form than that for the brass annular pipe. This fact is also found to be true for the flow of fluids in circular pipe. The explanation for this fact is that the greater shearing stress in the fluid in the rougher pipe requires a greater velocity gradient.

The effect of varying the ratio d_1/d_2 on the velocity distribution curves can be seen by examining the curves for the two steel annular pipes in Fig. 5. It should be realized that, although these pipes were made of the same material, their hydraulic roughnesses were different and therefore the effect of roughness is not entirely eliminated. The two curves practically coincide at all points from the core up to and including the point of maximum velocity. From the point of maximum velocity to the outer wall the curves diverge progressively, the pipe with the 3-in. core lying uppermost. The reason that these two curves were quite similar is probably a result of the fact that the values of the ratio d_1/d_2 did not vary appreciably in this investigation. Mr. Lorenz found a considerable change in the velocity distribution curve over a range of the ratio d_1/d_2 of 1.9 to 19.0. His results show a logarithmic dimensionless graph

giving the relations between the ratios—

$$\frac{\text{distance from core to point of maximum velocity}}{\text{distance from pipe wall to point of maximum velocity}} \quad \text{and} \quad \frac{d_1}{d_2}$$

—for three brass annular pipes. Mr. Lorenz found that the data for his three annular pipes fell approximately along a straight line. The point representing the data for the brass annular pipe used in this investigation did not fall along this line, however. According to Mr. Lorenz, as the ratio d_1/d_2 approaches unity, the point of maximum velocity approaches the midpoint of the annular space. The fact that no shift of the point of maximum velocity was noted in this investigation might be due to the narrow range of the values of d_1/d_2 used.

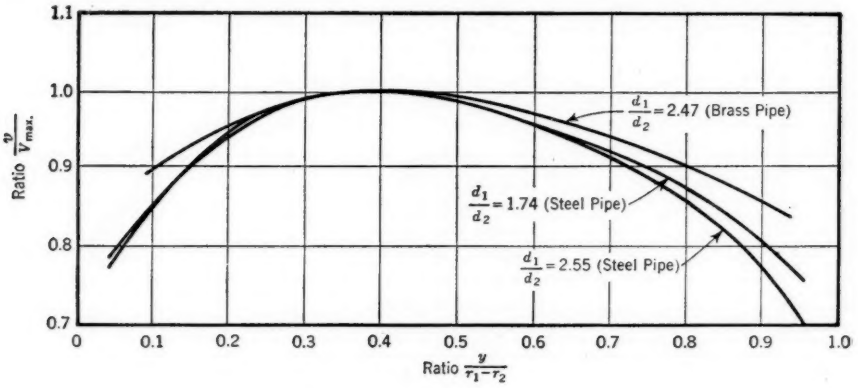

FIG. 5.—AVERAGE DIMENSIONLESS VELOCITY DISTRIBUTION CURVES

In order to find a mathematical expression for the velocity distribution curve the velocity data were plotted to logarithmic scales. This was done to determine whether or not the velocity distribution curve could be expressed as a simple exponential function, as is done in the case of pipes of circular cross section. Fig. 6 is a graph plotted to logarithmic scales showing the relation between the velocity v and distance from either the core or the wall for the three annular pipes used in this experiment. The open circles represent velocity distribution data for the region from the core to the point of maximum velocity, and the closed circles represent the data for the region from the pipe wall to the point of maximum velocity. The fact that these data for each velocity fall on two straight lines indicates that the equation for the velocity distribution curve is made up of two parts, one on each side of the maximum velocity and each having the form

$$v = a\, y^n$$

in which a is a constant and the other symbols are as previously defined. The value of n for the core is always equal to or less than that for the pipe wall and decreases with an increase in Reynolds number, with a few exceptions. This substantiates the statement made earlier that the velocity distribution curve appears to be a function of Reynolds number.

The difference in the slopes of the steel and brass annular pipes is caused mainly by the difference in roughnesses of the surfaces of the pipes. The value of n for the two steel annular pipes was found to decrease as the ratio d_1/d_2 decreases. This statement is in agreement with the conclusions given by Mr. Lorenz.

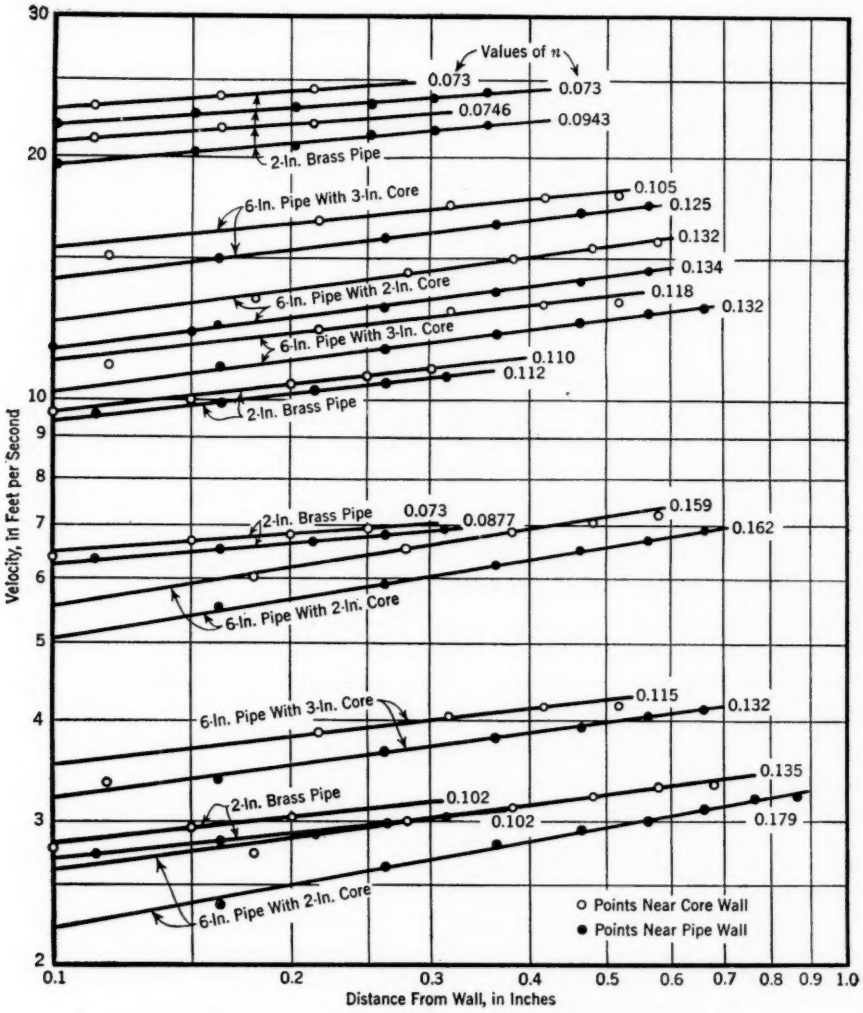

FIG. 6.—VELOCITY DISTRIBUTION CURVES NEAR CORE AND PIPE WALLS

CONCLUSIONS

From the results of this investigation the following conclusions can be drawn concerning the turbulent flow of water in the annular space between two coaxial cylindrical pipes for a range of values of d_1/d_2 from 1.76 to 2.55 and for a range of Reynolds numbers from 4,000 to 700,000.

Head Loss.—(1) The friction factor f for annular pipe is a function of Reynolds number, the roughness of the pipe, and the ratio d_1/d_2; (2) the friction factor at a given Reynolds number is greater for an annular pipe than for the outer circular pipe without the core; and (3) the friction factor, at a given Reynolds number, increases as the diameter of the core placed in the outer circular pipe increases.

Velocity Distributions.—(*a*) The point of maximum velocity of flow in an annular pipe lies approximately 0.4 of the distance between the core wall and pipe wall; (*b*) the velocity next to the core is always greater than that near the pipe wall; (*c*) the velocity distribution curve in an annular pipe is a function of the roughness of the surfaces; (*d*) the velocity distribution curve for a given annular pipe appears to be a function of Reynolds number; (*e*) the exponent n in the equation for the velocity distribution curve, $V = a\,y^n$, is less at the core wall than at the pipe wall; and (*f*) for annular pipes of the same hydraulic roughness the value of n in the equation for the velocity distribution curve is less for a smaller value of ratio d_1/d_2, therefore the velocity distribution is a function of the ratio d_1/d_2.

Acknowledgment

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APPENDIX I.—NOTATION

The following letter symbols have been adopted for use in this paper and in the discussion:

d_1 = inside diameter of outer pipe;
r_1 = inside radius of outer pipe;
d_2 = outside diameter of inner pipe;
r_2 = outside radius of inner pipe;
v = velocity at a given point;
V = average velocity of fluid;
V_{max} = maximum velocity of fluid;
g = acceleration of gravity;
f = friction factor in Darcy's equation, $h_f = f\dfrac{L}{R}\dfrac{V^2}{2g}$;
$\bar{R}$ = Reynolds number, $\bar{R} = \dfrac{4R\,V}{\nu}$;
h_f = head loss due to friction;
L = length of pipe test section;
μ = coefficient of viscosity;
ν = kinematic coefficient of viscosity;

A = cross-sectional area of annular section;
P = wetted perimeter;
R = mean hydraulic radius, $\frac{A}{P}$;
y = distance from core wall;
ϵ_1 = measure of roughness of outer pipe;
ϵ_2 = measure of roughness of inner pipe; and
n = an exponent, the slope of the velocity distribution curve in Fig. 6.

APPENDIX II.—BIBLIOGRAPHY ON FLOW IN ANNULAR PIPES

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CURRENT PAPERS AND DISCUSSIONS

Proceedings-Separate Number	Date Available	Title and Author	Discussion closes
50	Jan., 1951	"Supersonic Sounding Instruments and Methods," by Joseph M. Caldwell	June 1
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52	Feb., 1951	"Some Aspects of Electronic Surveying," by Carl I. Aslakson	July 1
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